An ASABE Meeting Presentation

Paper Number: 076189

FOOD POWDER DELIVERY THROUGH A FEEDER SYSTEM: EFFECT OF PHYSICO-CHEMICAL PROPERTIES

L. O. Pordesimo

Mississippi State University, Department of Agricultural and Biological Engineering, Box 9632, Mississippi State, MS 39762, U.S.A.

C. I. Onwulata

USDA-ARS-NAA-ERRC, Dairy Processing and Products Research Unit, 600 E. Mermaid Lane, Wyndmoor, PA 19038-8598, U.S.A

C. W. P. Carvalho

Embrapa Food Technology, Avenida das Américas 29501 - Guaratiba, 23020-470 Rio de Janeiro, RJ - Brazil

Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Mention any other presentations of this paper here, or delete this line.

Abstract. *As consumers have become more health conscious, there has been greater emphasis on improving the nutritional profile of foods or being able to deliver other health benefits through foods. For example, extruded snack foods, which are mostly starch-based, high-energy, low-nutrient-dense foods have been implicated as contributing toward the higher incidence of obesity and diabetes in the U.S., are benefiting of recent improvements through fortification with whey protein. Successful incorporation of whey protein into extruded snack products will improve the nutrient density of these snacks by increasing protein content and also presents an alternative avenue for higher value utilization of whey proteins. Other than formulation, another critical aspect in the production of "healthy" snacks is the delivery of raw material to a mixer, or even an extruder, in the correct ratio and concentration. The need for specification and accurate prediction of powder behavior in* *handling and processing equipment is certainly becoming more compelling in a market environment with greater health concerns and quality expectations. Equations involving powder physical and chemical properties were developed to predict their delivery by a commercial twin screw feeder. Computation with these equations eliminates the need for time-consuming calibration studies for each powder handled undertaken in industry.*

Keywords. Food powders, screw feeder, physical properties, delivery rate

Introduction

In the food industry alone there is an increasing variety and quantity of powders and granular material being produced. These would either be final processed food products or ingredients for other complex foods being produced today. Handling and such other process unit operations as formulation and mixing are keys in efficiently and effectively blending and utilizing those ingredients to make healthful and nutritious foods. As consumers have become more health conscious, there has been greater emphasis on improving the nutritional profile of foods or being able to deliver other health benefits through foods. For example, extruded snack foods, which are mostly starch-based, high-energy, low-nutrient-dense foods have been implicated as contributing toward the higher incidence of obesity and diabetes in the U.S., are benefiting of recent improvements through fortification with whey protein (Matthey and Hanna, 1997; Onwulata et al., 1998; Onwulata et al., 2001a; Onwulata et al., 2001b; Singh et al., 1991). Successful incorporation of whey protein into extruded snack products will improve the nutrient density of these snacks by increasing protein content and also presents an alternative avenue for higher value utilization of whey proteins. This potentially increases the utilization of whey products in foods, which is still below 50% of total production (American Dairy Products Institute, 2005).

In automated blending or mixing operations, the feed powder delivery system is critical towards the production of uniform formulations. It is used to provide raw material to a mixer, or even an extruder, in the correct ratio and concentration. When properly selected, the feed system provides reliable, predictable, and controllable solids flow to other downstream food processes. The feeder, or flow promotion device in general, a device to control the flow of bulk solids from a storage/holding bin, is the heart of the feed system. A feeder, usually rated by manufacturers on the basis of volume capacity, must be selected to suit a particular bulk solid and the range of feed rates required. To work in unison with the bin, the feeder must suit the material flow properties, withdraw the material uniformly across the outlet's cross-sectional area, minimize the load the material applies to the feeder, and accurately control the discharge or delivery rate (Marinelli, 1996). Oftentimes, however, there is already a feeder in place and its operation has to be controlled with respect to the type of powder to be delivered. Screw feeders are quite useful in producing uniform feed rates for a variety of bulk solids and they use very simple components. As a result, they are widely used in the food industry. Twin screw feeders, in particular, are used to handle more difficult materials like sticky materials, pigments, fiber and fiberglass, and bridging or flooding powders.

The need for the specification and accurate prediction of powder behavior in handling and processing equipment is certainly becoming more compelling in a market environment with greater health concerns (O'donnell and O'donnell, 2006) and quality expectations. However, in the least, understanding the differences in delivery by the flow promotion device as affected by the powder properties will be valuable. Not much is written about this in the scientific literature. Researchers have focused on evaluating the flowability or flow properties of powders as an intrinsic property of the powder (Peleg et al., 1973; Sjollema, 1963; Teunou and Fitzpatrick, 1999; Teunou et al., 1999), independent of the flow promotion device. Information, even if specific to a particular flow promotion device, will certainly be of great practical value because it can serve as a reference basis for equipment selection or adjustment of equipment operational settings by engineers and technicians. For instance, in their study, Hoffmann et al. (1996) related the behavior of powders in precision handling apparatus with the fundamental properties of the constituent particles of powders. As such, the objectives of this research were:

1. To measure and quantify the delivery of different types of food powders in a twin screw feeder at increasing feeder settings.

2. To analyze the effect of physico-chemical properties on powder delivery by this mechanized conveying system.

Materials and Methods

Powders

The food powders studied fell into three broad categories: 1) cereal powders, 2) milk powders, and 3) whey powders. All 14 products tested were procured commercially. Cereal powders included meal, flours, and starches; these were corn meal (Agricor, Inc., Marion, Ind.); corn starch (Tate & Lyle North America, Decatur, Ill.); and corn (Agricor, Inc., Marion, Ind.), barley (ConAgra Foods, Omaha, Neb.), oat (ConAgra Foods, Omaha, Neb.), soy (Cargill Soy Protein Solutions, Cedar Rapids, Iowa), and wheat (ConAgra Mills, Omaha, Neb.) flours. Non-fat dry milk (DairyAmerica, Fresno, Cal.) was taken as the representative milk powder. Whey powders consisted of sweet whey (Dairy Farmers of America, Inc., Kansas City, Mo.), whey protein concentrates (WPC 34 - Dairy Farmers of America, Inc., Kansas City, Mo.; WPC 75 – CALPRO Ingredients, Corona, Cal.; WPC 80 – Davisco Foods International, Inc., Eden Prairie, Minn.), and whey protein isolates (WPI 190, WPI 192 – Glanbia Nutritionals, Monroe, Wisc.).

Flour is a fine powder made from cereals or other starchy food sources. Most commonly flour is made from wheat, but flours from corn rye, barley, and rice, amongst many other grasses and non-grain plants are also manufactured. Whole grain flours (wheat and whole oat flours) are produced by grinding or mashing the whole grains. The word “whole” refers to the fact that all of the grain (bran, germ, and endosperm) is used and nothing is separated nor lost in the process of making flour. Malted barley flour is the product of grinding barley grains that have been allowed to germinate and then quickly dried before the plant develops. A coarser, somewhat granular preparation, rather than a fine powder, is often called meal and that is the case with corn meal. Cornstarch is the material made by pulverizing ground, dried residue of corn grains after preparatory soaking and removal of the embryo and the pericarp. Applications of cornstarch include thickeners, bulking agents into laundry, and binding ingredients in adhesives.

Nonfat dry milk (NFDM), also known as Dried Skim Milk (DSM), is the product resulting from the removal of fat and water from pasteurized, fresh cow’s milk and contains lactose, milk proteins, and milk minerals in the same relative proportions as in fresh milk from which it is made. It contains not over 5% by weight of moisture. The fat content is not over 1.5% by weight unless otherwise indicated.

Sweet whey is obtained by drying fresh whey (derived during the manufacture of cheeses such as Cheddar and Swiss) that has been pasteurized and to which nothing has been added as a preservative. In the cheese making process there is insignificant conversion of lactose to lactic acid. Whey protein concentrate is the substance obtained by the removal of sufficient non-protein constituents from pasteurized whey so that the finished dry product contains more than 34% protein. Whey protein concentrate (WPC) is produced by physical separation techniques such as precipitation, filtration, or dialysis. Whey protein isolate (WPI) is the substance obtained by the removal of sufficient non-protein constituents from whey so that the finished product contains not less than 90% protein on an air dry basis. WPI 192 is an agglomerated version of WPI 190.

Powder Physico-chemical Properties

Considering that in a very simplistic sense powder flow dynamics is affected by powder properties as represented by the relationship

$$flow\ dynamics = f\,(particle\ density,\ particle\ size,\ particle\ shape,\ bulk\ density,\ composition) \tag{1}$$

Some of the physical and chemical properties of the powders were measured to provide an understanding of the effect of their variation on powder delivery through a feeder system. Property measurements were made in triplicate except for the bulk densities, which were measured from eight different samples.

Moisture and fat are chemical components of powders and granular materials that can cause cohesion between powder particles and are therefore related to flow behavior. Both these powder compositional components were determined using AOAC standard methods (2000). Moisture content was determined by drying under vacuum for 4 hr at 102°C. Fat content was determined by first placing a 1-g sample in an Ehrlenmeyer flask. One mL of sulfuric acid and 4 mL of water were added to a flask and the contents were then mixed gently. After 60 min., the contents of the flask were transferred to a 60 mL separatory funnel using 25 mL of dichloromethane:methanol solution (1:1). After another 15 min., the bottom layer, which is the extract containing fat, was drained into a weighing pan and then evaporated. The amount of fat was then calculated as a percent of the original sample weight.

Both loose and tap bulk density of the test materials were determined. The loose bulk density of all test materials was determined by dividing the weight of powder delivered freely by gravity into a 200-mL stainless steel cylinder by its volume. Tap bulk densities were calculated from the weight of powder contained in the cylinder after being hand tapped 100 times at roughly 60 taps/min. The foregoing test cylinder had a removable extension that was carefully removed after the tapping, leaving a 100 mL volume for tap density calculation. In both cases excess powder was scraped from the top of the fixed volume container by sliding a wooden straight edge in a zigzag fashion across the container rim so that the material surface was flush with the container rim. Care was taken so as not to disturb or compact the settled powder. All bulk density measurements were made in triplicate. Compaction of the powders was described by the "Hausner ratio," the ratio of the tap bulk density to the loose bulk density. The Hausner ratio is frequently used as a relative flowability index.

Apparent particle density was determined with an air pycnometer (Horiba Model VM-100, Horiba, Inc., Irvine, Cal.). Apparent particle density, simply referred to as particle density in this report, is the mass of a particle divided by its volume, excluding only the open pores.

Particle size distribution (PSD) was determined for the test materials using an Accusizer Optical Particle Sizer Model 770 (Particle Sizing Systems, Santa Barbara, Cal.). Samples were fed using a vibratory feeder and number-weighted as well as volume-weighted measures of central tendency (mean, median, mode) for the differential particle size frequency distribution were determined. The volume weighted PSD emphasizes the large particles while the number weighted PSD emphasizes the fines. Results of the particle size analysis for each powder were also expressed graphically as an undersize cumulative frequency curve and, based on that, particle diameters representing the cutoff particle diameter for 25, 50, and 75% of the particles (D numbers), respectively, were determined.

Angle of repose was measured by the pouring method (Teunou et al., 1995). Fayed and Otten (1984) defined angle of repose in general as "the angle formed between the horizontal plane and a slope line extending along the face of a heap formed by pouring material onto a horizontal surface." Powder was allowed to flow through a conical funnel having a spout diameter of 2 cm. The angle of repose was calculated from the base angle formed by the heap of powder (Sjollema, 1963).

According to Wouters and Geldart (1996), the angle of repose can provide the process engineer quickly with valuable information. Therefore, since the tests can be performed in the plant, the angle of repose is taken as a predictor of possible flow difficulties later in industrial applications

Barbosa-Canovas et al. (2005) also forwarded that the angle of repose can be used as a rough flowability indicator. In fact, they noted that it is the actual measurement applied by food industry quality control in order to evaluate flowability. According to Carr (1976) angles of up to 35 indicate free flowability, 33-45 some cohesiveness, 45-55, cohesiveness (loss of free flowability) and 55 and above very high cohesiveness and, therefore, very limited (or no) flowability. This characterization method can provide a rough flow indication on small quantities of powders that have not undergone any consolidation.

Feeder Delivery

Tests on feeder delivery at different device settings were thus undertaken using a twin screw volumetric feeder rated at 22.7 kg h-1 as the test platform. The feeder was equipped with twin concave profile 35 mm screws designed to deliver particles with a maximum diameter of 1.52 mm. The feeder hopper was loaded with 10 kg of material and, as best possible, a consistent head of material was maintained. Feeder delivery could be adjusted by varying its motor speed. The maximum motor speed setting for the test platform was 2000 rpm; therefore, samples were collected at 100 rpm increments till the maximum 2000 rpm was reached. After each speed adjustment, delivery was allowed to stabilize before throughput samples were collected by allowing the feeder to run for 5 min. All samples were collected over 2 min. except in the case of WPIs which were collected over 1 min. only and weights were recorded in grams. Powder delivery tests over the range of selected feeder settings were replicated three times.

Statistical Analysis

Regression analysis was conducted using the REG procedure in SAS® v9.1.3 (SAS Institute, Inc., Cary, N.C.) to model the increasing relationship between powder delivery and feeder setting. Regression analysis was undertaken to first determine the appropriateness of a linear model to represent variation in powder delivery with increasing feeder setting. Secondly, regression analysis was used to compare the delivery rate linear relationships among the 14 powders examined in the study and, more specifically, to determine if the linear slopes varied with the type of material delivered. Differences in the linear models for the different test powders were further investigated through an analysis of variance using the MIXED procedure in SAS implementing orthogonal polynomial contrasts. Effects of powder properties on the linear slopes of the powder delivery-feeder setting relationships were then explored though multiple regression.

Results and Discussion

Powder Characterization

Results of the physical and chemical property measurements of the various powders are presented in Tables 1-4. The powder properties measured were grouped as chemical properties (MC, fat), particle physical properties (particle density; D25; D50; D75 from a particle size cumulative frequency distribution; mean, median, and mode of a number-weighted particle size differential frequency distribution; mean, median, and mode of a volume-weighted particle size differential frequency distribution), and bulk properties (loose bulk density, tap bulk density, Hausner ratio, and angle of repose). Similar to Tenou et al (1999), a number of powder physical and chemical properties were measured not only because they provide an understanding of their delivery through a screw feeder but also because they define the test materials.

For data analysis, the test powders were broadly grouped as cereals or dairy powders at the highest level of integration. Within cereals there were starches, flours, and meals while within dairy powders there were WPIs, WPCs, dry whole whey (sweet whey), and dry milk (NFDM). Graphical presentation of the measured cereal or dairy powder properties was sequenced according to estimations of increasing particle size (Fig. 1).

As shown in Fig. 1A, the cereal powders (cornstarch, corn flour, and corn meal) were higher in moisture followed in turn by dry milk and sweet whey then whey protein powders (concentrates and isolates). At moisture content levels greater than 8%, the cereal powders are essentially considered wet while the dairy powders with moistures less than 4% are relatively dry. Sweet whey and NFDM were distinctly higher in fat content than all other product types.

Particle density and particle size relate to give mass of the powder. These measurements are shown in Fig. 1B-1C. Interestingly, the particle densities shown in Fig. 1b of product types within the broad groupings are not markedly different despite the products differing in composition. The cereal powders had an average particle density of 1493.34 kg m^{-3} while milk and the whey powders had average particle densities of 1362.33 and 1227.81 kg m^{-3}, respectively. The particle size results for dairy powders presented in Figs. 1B and 1C show a generally consistent increase in particle size from milk to whey to WPC with the results for WPI falling below the results for both WPC and whey. Meanwhile, for cereal powders, the trend for both D50 and the number-weighted PSD mean was increasing from starch to meal while the opposite trend was observed for the volume-weighted PSD mean. The later result for cereals is a further indication that the cereal products tested had a fairly wider size distribution.

The salient information shown in Fig. 1D is that there appears to be a consistent difference between loose and tap bulk density for all powders except for meal, which was smaller.

Powder Delivery Rate

Delivery rates for the different tested powders through a twin screw feeder over progressive incremental settings of the feeder drive motor (feeder setting) are shown in Fig. 2. As illustrated for all materials tested, there was linearity between powder delivery by a twin screw feeder and feeder setting. The direct proportionality of powder delivery to feeder rotational speed is intuitive and is a result that is consistent with all other studies (Rautenbach and Schumacher, 1987) especially for well designed devices with excellent metering characteristics. It is also apparent from the figure that delivery rates varied with the material conveyed. These two observations were confirmed statistically through the advanced regression techniques: lack of fit ($P < 0.001$) and dummy regression ($P < 0.001$), respectively. Thus, powder delivery by a twin screw feeder can be aptly represented by the relationship

$$delivery = a + b * (feeder\ setting) \tag{2}$$

where feeder setting in this study was motor speed and the slope b depends on the material delivered (Fig. 3). Linear regression parameters relating feed rate to feeder setting for each of the test powders are listed in Table 5. Noticeably, the linear regression slopes for the cereal powders are an order of magnitude greater than slopes for the dairy powders. The results presented show that the y-intercept can essentially be taken as zero (0). However, a fundamental issue that needs to be addressed is how to directly integrate material properties into this relationship or, at least, develop an algorithm to account for powder property effects.

Table 1. Test powder fat and oil content

Product	MoistureContent (%)	Fat Content (%)
Corn starch	11.34±0.08	1.88±0.25
corn meal	8.41±0.29	0.58±0.25
corn flour	12.45±0.12	1.56±0.21
barley flour	4.63±0.01	2.83±0.49
oat flour	10.24±0.08	5.05±1.18
soy flour	5.68±2.49	2.49±0.48
wheat flour	11.98±0.08	1.87±1.02
NFDM	2.50±0.06	1.34±0.51
sweet whey	1.63±0.03	1.99±0.54
WPC34	4.62±0.08	3.72±0.80
WPC75	3.11±0.21	6.50±2.16
WPC80	3.70±0.12	10.43±4.08
WPI190	4.86±0.10	9.06±4.35
WPI192	2.97±0.13	-

Table 2. Particle size (µm) statistical parameters from differential frequency distributions

	Number-weighted			Volume-weighted		
Product	Mean	Mode	Median	Mean	Mode	Median
cornstarch	193.66	5.42	23.28	3008.90	3868.51	3163.54
corn meal	259.84	5.42	119.98	1125.82	2176.32	981.93
corn flour	215.54	37.83	93.13	2395.09	3719.51	2329.11
barley flour	187.48	37.83	69.77	2526.71	4046.87	2578.28
oat flour	290.42	37.83	124.14	2274.29	4215.92	2094.38
soy flour	198.09	37.83	39.10	1610.85	2599.00	1599.07
wheat flour	139.34	37.83	74.46	1236.95	3105.12	1038.29
NFDM	86.64	37.83	50.20	2434.68	3404.02	2928.49
sweet whey	126.22	37.83	39.10	2401.94	4046.87	2683.73
WPC34	97.42	37.83	37.44	2226.77	4368.94	1838.77
WPC75	221.00	15.49	27.16	3463.21	4226.01	3654.43
WPC80	291.72	37.83	37.05	3252.81	3961.93	3323.02
WPI190	107.09	37.83	34.75	1668.94	2622.05	1714.11
WPI192	-	-	-	3008.90	3868.51	3163.54

Table 3. Particle density and particle size parameters from a cumulative particle size frequency distribution

Product	Particle Density (kg m^{-3})	Undersize Cutoff Particle Sizes (µm) 25%	50%	75%
cornstarch	1498.87±0.42	7.35±1.36	22.87±0.71	73.05±7.06
corn meal	1486.35±0.23	24.48±2.52	119.91±10.00	421.59±13.02
corn flour	1491.36±7.15	30.92±2.18	92.79±6.214	220.62±6.81
barley flour	1616.72±5.27	26.88±2.11	76.84±11.32	191.17±10.32
oat flour	1450.72±6.80	34.34±1.95	124.14±6.70	393.82±43.10
soy flour	1443.27±0.39	19.61±3.18	38.97±2.76	202.98±29.89
wheat flour	1471.99±0.86	32.18±0.00	74.76±2.02	171.45±0.00
NFDM	1362.33±0.54	35.47±2.87	72.17±16.03	142.64±25.10
sweet whey	1225.32±3.23	50.30±12.31	83.64±29.39	154.34±31.81
WPC34	1223.39±0.41	19.61±3.18	39.27±2.50	110.67±8.81
WPC75	1192.11±31.00	11.22±0.24	30.50±2.21	70.03±7.66
WPC80	1236.33±3.76	17.77±0.00	36.73±0.42	153.70±15.36
WPI190	1267.07±5.42	17.77±0.00	36.82±0.69	102.39±14.06
WPI192	1214.61±7.19	-	-	-

Table 4. Test material bulk properties

Product	Bulk density (kg m^{-3}) loose	tap	Hausner ratio	Angle of repose (deg)
cornstarch	492±7.89	632±6.32	1.28±0.02	39.33±0.77
corn meal	655±7.07	718±9.19	1.10±0.01	26.24±1.13
corn flour	488±9.72	677±12.52	1.52±0.41	37.83±2.90
barley flour	511±5.68	684±9.66	1.34±0.01	31.32±2.60
oat flour	401±3.16	543±4.83	1.35±0.01	40.11±4.78
soy flour	394±11.74	414±12.65	1.05±0.02	31.26±1.56
wheat flour	549±24.70	709±31.43	1.29±0.01	30.86±0.00
NFDM	506±10.75	663±8.83	1.31±0.02	21.78±3.16
sweet whey	506±5.16	625±5.27	1.24±0.02	31.11±4.09
WPC34	458±6.32	601±5.68	1.31±0.02	27.09±1.06
WPC75	274±8.43	377±6.75	1.38±0.04	49.99±1.13
WPC80	271±3.16	366±6.99	1.35±0.03	50.79±0.00
WPI190	255±5.27	321±5.68	1.26±0.03	47.14±5.16
WPI192	248±11.35	452±13.98	1.82±0.06	-

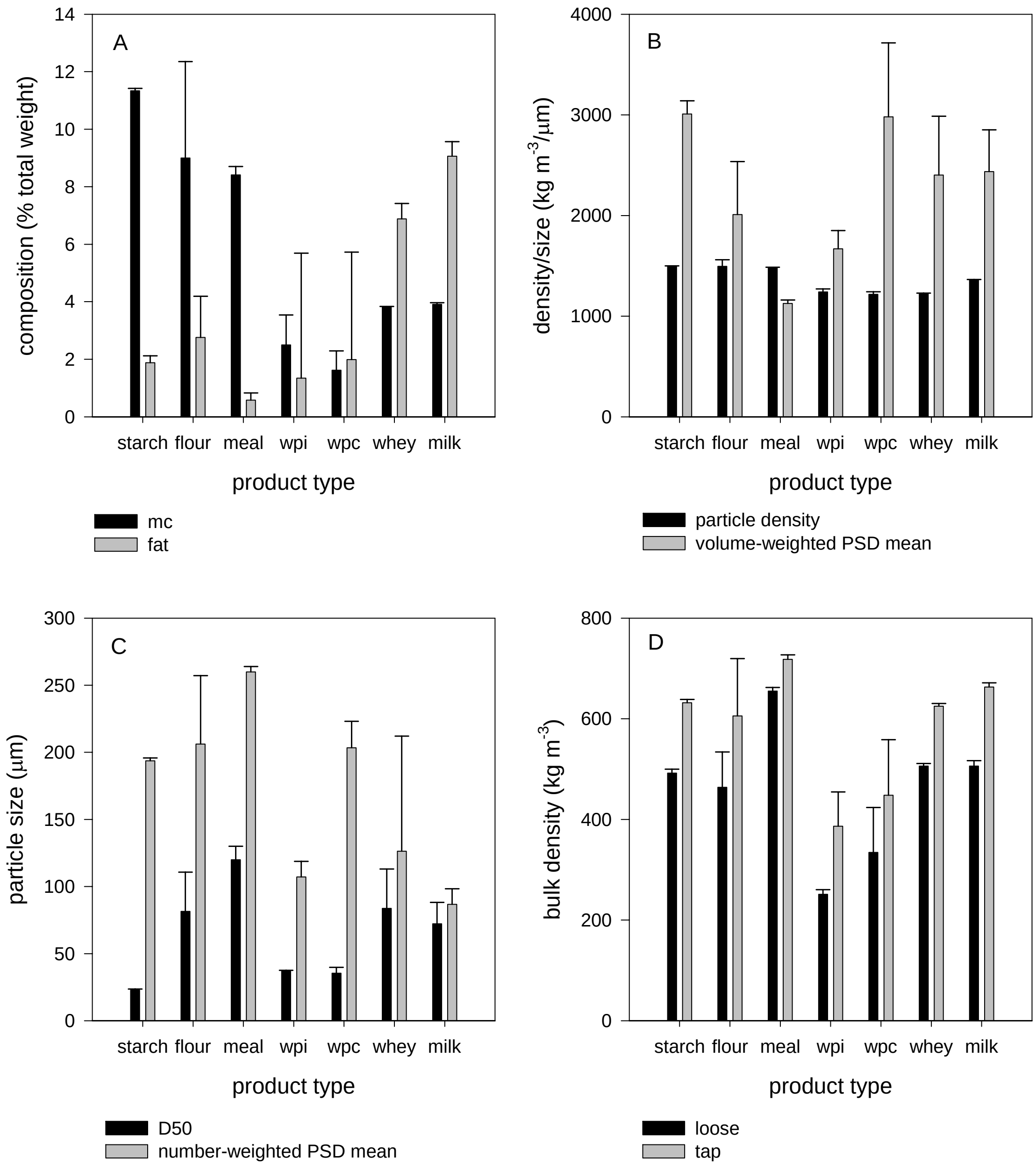

Fig. 1. Physico-chemical properties of the different food powder types tested

A more fundamental study would have been to measure powder delivery at increasing feeder settings and compare that to the theoretical volumetric capacity of the feeder based on its dimensions/specifications and the assumed plug flow delivery of an incompressible powder. Such a study would have isolated the effect of material type on delivery rate. However, considering that core diameters, screw diameters, and screw pitch interact intimately with such material properties as coefficient of friction on the screw and housing material, calculation of theoretical capacity is not simplistic. As a first step, it would have involved specifying some kind of “ideal” powder or reference material. In this regard, Rautenbach and Schumacher (1987) noted that although screw feeders have been employed for many years in industry, dependable, theory-based design equations for calculation of delivery and power consumption do not exist. For these reasons, the study was limited to be purely empirical in nature, similar to the pioneering work of Burkhardt (1967) with screw conveyors.

Material Influences on Powder Delivery

Trend analysis using orthogonal polynomial contrasts indicated that the delivery rate of cereals by the twin screw feeder was greater than the delivery of milk powders ($P < 0.001$) over the feeder settings. Among dairy powders, the linear regression relationship between delivery rate and feeder setting was different among NFDM, sweet whey, WPC, and WPI ($P < 0.001$). Among cereals, the linear regression relationship between delivery rate and feeder setting was different among starch, flour, and meal ($P < 0.001$). These results further confirm that powder properties affect delivery rates.

Sixteen physico-chemical properties were measured to characterize the powders and to understand their mechanical flow rate. As a means of determining which of the measured 16 physico-chemical properties had greater effects on the measured delivery rates, multiple regression was undertaken. Specifically, the relationship between powder properties and the slopes of the linear equations relating delivery rate for each powder at different screw feeder settings was investigated. A 3-variable model involving particle density (ρ_p), D50, and the mean of the volume-weighted PSD $(\bar{x}_3)$ had an R-square of 92.26%. The change in the R-square from a 3-variable model to a 4-variable model with mean particle size from a number weighted PSD as an added variable was only 0.01% so the 3-variable model was deemed the best alternative expressing the observed trends in screw feeder delivery rate trends. Therefore, in this study, among the powder properties measured, particle density and particle size adequately accounted for the influence of material differences on powder delivery by a screw feeder:

$$slope = -1.990E{-}3 + 2.310E{-}6 * \rho_p + 3.240E{-}6 * D50 - 2.246E{-}7 * \bar{x}_3 \qquad (3)$$

The multiple regression results also revealed that particle density alone accounted for 80.9% of the variation in the linear regression slopes while D50 and the mean of a volume weighted PSD individually accounted for 31.2% and 52.4% of the variability, respectively. The nature of the relationship of these properties to the linear slopes is shown in the scatter plots of Fig. 4. There was more of a direct relationship between the regression slopes and particle density, but an inverse relationship with the mean of the volume-weighted PSD. These two particle properties affect space filling. For a given particle density, coarse particles occupy more space while fine particles tend to be more dense (Barbosa-Canovas et al., 1987). Considering that a screw feeder essentially delivers a fixed volume of material, it logically follows that a denser granular mass will result in a higher delivery rate expressed on mass per unit time basis. Although bulk density actually accounts for these two particle properties together, it did not significantly contribute to explaining the differences in powder delivery by the twin screw feeder according to the multiple regression analysis (3.5%). It is possible then that there were errors in measuring bulk density. Bulk density measurement required much more manual manipulation to accomplish than the instrumented measurements of specific particle properties. In consequence, bulk density measurement is likely to be much more prone to human error.

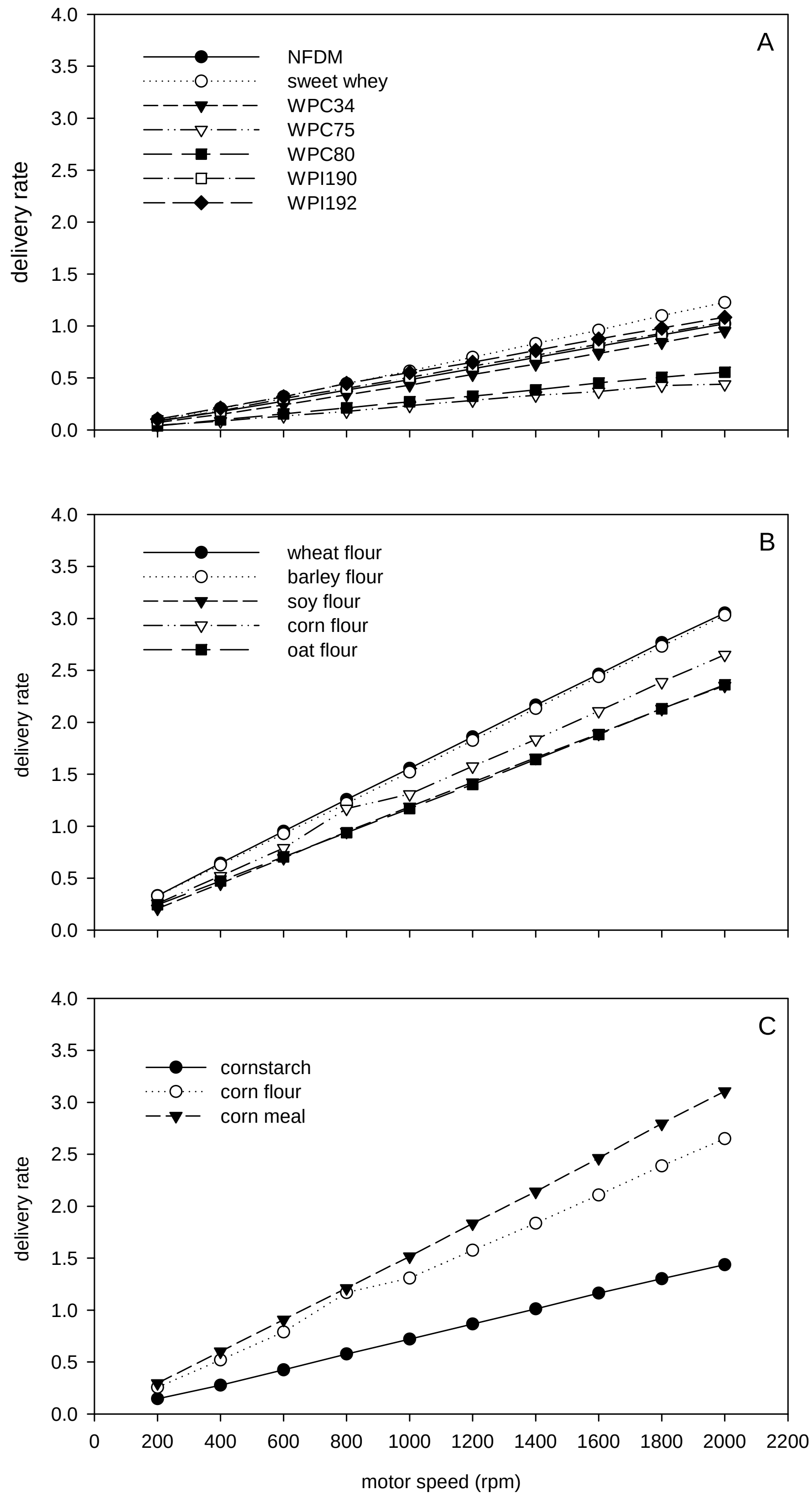

Fig. 2. Powder delivery of different food powders at increasing twin screw feeder settings

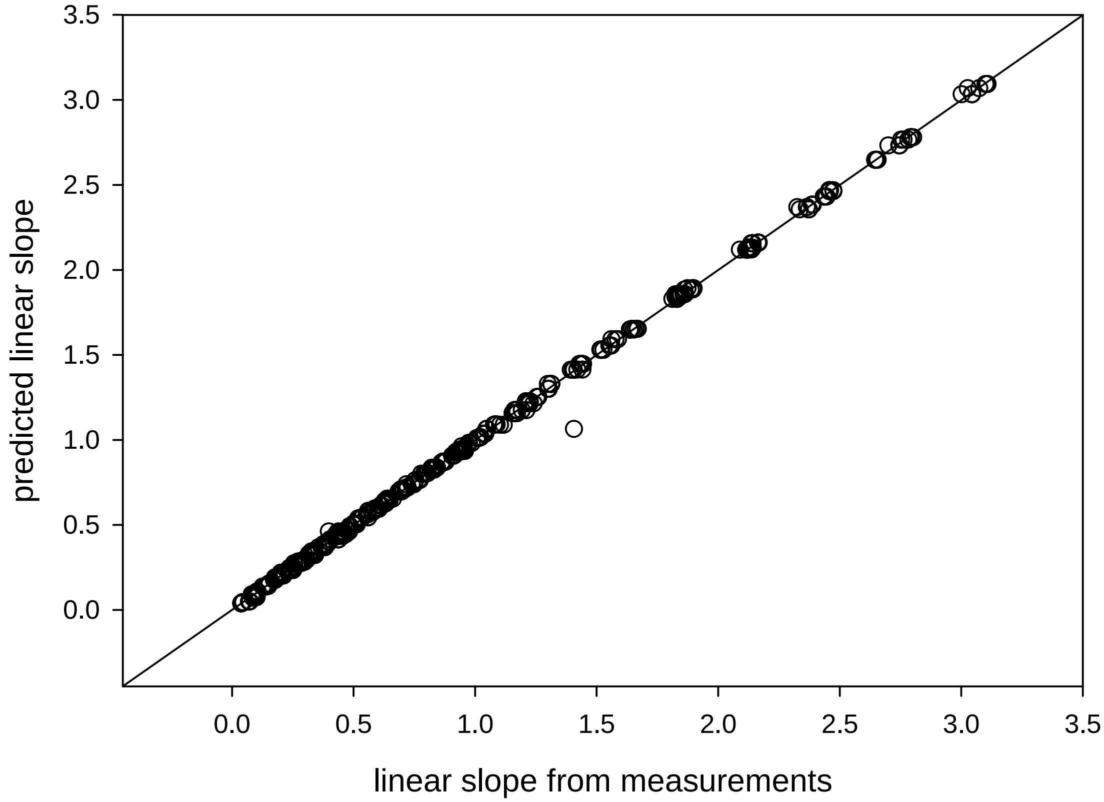

Fig. 3. Relationship between measured and predicted powder delivery rates for a twin screw feeder

Material influences on powder delivery by the twin screw feeder can be accounted as component terms in the prediction of the slope (Eq. 2). Having measured the influential powder particle properties, the slope of the linear relationship of powder delivery to the twin screw feeder setting (Eq. 1) can be calculated using Eq. 2. Feeder setting to give the desired delivery rate for a process can then be simply calculated by back substitution into Eq. 1. Since the feeder setting in this study was actually the feeder drive motor speed in rpm, the relationships presented are probably only effective for the test twin screw feeder. The relationships would have been much more general if they involved actual screw speed. In succeeding work, actual screw speed at a given motor speed setting will have to be calculated or directly measured. Despite this limitation, the study results are still valuable as a reference basis for equipment selection or adjustment of equipment operational settings by engineers and technicians. The study is also limited in addressing delivery of pure powders only and not mixtures.

As shown in Fig. 2 and confirmed by trend analysis within the analysis of variance, there was no difference in the powder deliver-feeder setting relationships between barley and wheat flour and between oat flour and soy flour. In a way this is perplexing because these flours originated from very differentiated crops, in fact, soybean is not a cereal but is rather a legume. However, scanning through the particle density measurements and particle size parameters, this finding appears to be more in line with the general trends observed for the product type groupings. For instance, barley and wheat flours had particle densities of 1616.72 and 1471.99 m^{-3}, respectively, compared to the relatively lower 1450.72 kg m^{-3} for oat flour and 1443.27 kg m^{-3} for soy flour. D75 for barley flour was 191.17 µm compared to 171.45 µm for wheat flour while the D75 for oat flour was 393.82 µm compared to the 202.98 µm for soy flour. There was also a close comparison among the bulk density measurements for these products (Table 4).

Conclusion

For well-designed devices with excellent metering characteristics, like the test platform used, this study reaffirms that there is a direct proportionality between delivery rate for different non-consolidated, non-cohesive powders over progressive incremental settings of the feeder. In this study, there was a clear linearity between powder delivery by the twin screw feeder over its entire operating range with the rate varying with the material delivered. Out of the 16 powder physico-chemical properties measured, apparent particle density and particle size represented by both D50 and the mean of volume weighted PSD accounted for the difference in the linear slopes of the delivery rate-feeder setting relationships. Effects of these powder properties on delivery by the twin screw feeder can be accounted for as component terms in the prediction of the slope of the delivery rate-feeder setting linear relationship. (Eq. 2).

Acknowledgements

The advice and assistance of Dr. John Philips on statistical analysis is gratefully appreciated.

Table 5. Powder delivery-feeder setting linear regression parameters

Product	Intercept (kg s^{-1} x 10^3)	Slope ((kg s^{-1} x 10^3)/rpm)
cornstarch	-3.3296E-02	5.2373E-04
corn meal	-4.9630E-01	4.9201E-04
corn flour	-2.7222E-03	2.3162E-04
barley flour	-2.0963E-02	2.9062E-04
oat flour	-2.2741E-01	5.2911E-04
soy flour	-3.2593E-03	5.4678E-04
wheat flour	2.2574E-02	1.5048E-03
NFDM	9.5000E-03	1.3181E-03
sweet whey	-3.0926E-02	1.5615E-03
WPC34	-5.5370E-03	7.2536E-04
WPC75	-2.5000E-03	1.1786E-03
WPC80	2.1037E-02	1.1948E-03
WPI190	-5.2259E-02	6.3334E-04
WPI192	3.9455E-02	1.5142E-03

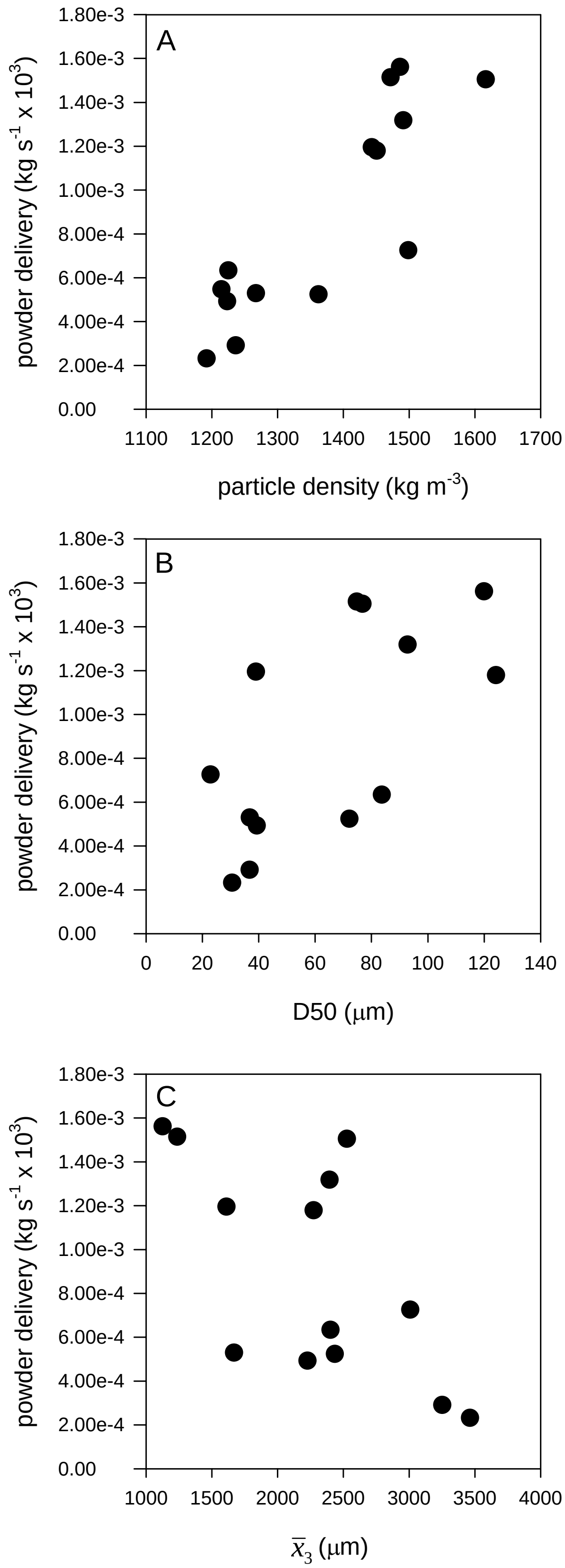

Fig. 4. Relationship of particle density and particle size to the linear slopes of the powder delivery-feeder setting relationships

References

American Association of Cereal Chemists. 2000. Approved Methods of the American Association of Cereal Chemists. 9th ed. American Association of Cereal Chemists, St. Paul, Minn.

American Dairy Products Institute. 2005. Dairy products: Utilization and production trends 2004. American Dairy Products Institute, Elmhurst, Ill.

Barbosa-Canovas, G.V., J. Malave-Lopez, and M. Peleg. 1987. Density and compressibility of selected food powder mixtures. J. Food Process Eng. 10:1-19.

Barbosa-Canovas, G.V., E. Ortega-Rivas, P. Juliano, and H. Yan. 2005. Food Powders: Physical Properties, Processing, and Functionality Kluwer Academic/Plenum Publishers, New York.

Burkhardt, G.J. 1967. Effect of pitch, radial clearance, hopper exposure and head on performance of screw feeders. Trans. ASAE 10:685-690.

Carr, R.L. 1976. Powder and granule properties and mechanics, In J. M. Marchello and A. Gomezplata, eds. Gas-Solids Handling in the Processing Industries. Marcel Dekker, New York.

Fayed, M.E., and L. Otten. 1984. Handbook of Powder Science and Technology Van Nostrand Rheinhold Company Inc., New York.

Hoffmann, A.C., H.J. Finkers, and J.A. Seegers. 1996. Relationship between particle properties and bulk behaviour for some industrial powders. Part. Part. Syst, Charact. 13:354-361.

Marinelli, J. 1996. Choosing a feeder that works in unison with your bin. Powder Bulk Eng. 10:43-57.

Matthey, F.P., and M.A. Hanna. 1997. Physical and functional properties of twin-screw extruded whey protein concentrate-corn starch blends. Lebens. -Wiss. U. -Technol. 30:359-366.

O'donnell, J.A., and C.D. O'donnell. 2006. Building better foods and supplements. Prepared Foods 175:NS3-NS4,NS6, NS8,NS10-NS11.

Onwulata, C.I., R.P. Konstance, P.W. Smith, and V.H. Holsinger. 1998. Physical properties of extruded products as affected by cheese whey. J. Food Sci. 63:814-818.

Onwulata, C.I., R.P. Konstance, P.W. Smith, and V.H. Holsinger. 2001a. Incorporation of whey products in extruded corn, potato or rice snacks. . Food Res. Int. 34:679-687.

Onwulata, C.I., R.P. Konstance, P.W. Smith, and V.H. Holsinger. 2001b. Co-extrusion of dietary fiber and milk proteins in expanded corn products. Lebensm.-Wiss. u.-Technol. 34:424-429.

Peleg, M., C.H. Mannheim, and N. Passy. 1973. Flow properties of some food powders. J. Food Sci. 38:959-964.

Rautenbach, R., and W. Schumacher. 1987. Theoretical and experimental analysis of screw feeders. Bulk Solids Handling 7:675-680.

Singh, R.K., S.S. Nielsen, J.V. Chambers, M. Martinez-Serna, and R. Villota. 1991. Selected characteristic of extruded blends of milk protein raffinate of nonfat dry milk with corn flour. J. Food Proc. and Preserv. 15:285-302.

Sjollema, A. 1963. Some investigations on the free-flowing properties and porosity of milk powders. Neth. Milk Dairy J. 17:245-259.

Teunou, E., and J.J. Fitzpatrick. 1999. Effect of relative humidity and temperature on food powder flowability. J. Food Eng. 42:109-116.

Teunou, E., J. Vasseur, and M. Krawczyk. 1995. Measurement and interpretation of bulk solids angle of repose for industrial process desgin. Powder Handling Process. 7:21-27.

Teunou, E., J.J. Fitzpatrick, and E.C. Synnott. 1999. Characterization of food powder flowability. J. Food Eng. 39:31-37.

Wouters, I.M.F., and D. Geldart. 1996. Characterising semi-cohesive powders using angle of repose. Part. Part. Syst. Charact. 13:254-259.